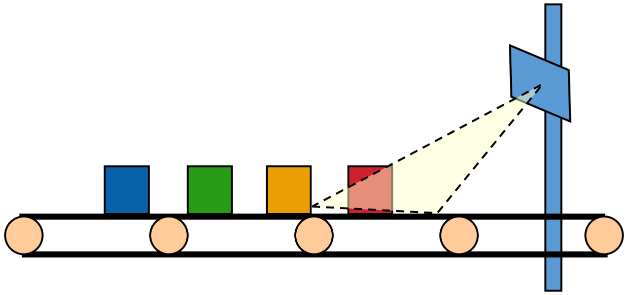
Tagoram: Real-Time Tracking of Mobile RFID Tags to High-Precision Accuracy Using COTS Devices

Xiang-Yang Li

Lei Yang, Yekui Chen, Xiang-Yang Li,
Chaowei Xiao, Mo Li, Yunhao Liu

Sep. 9, 2014

Tsinghua University



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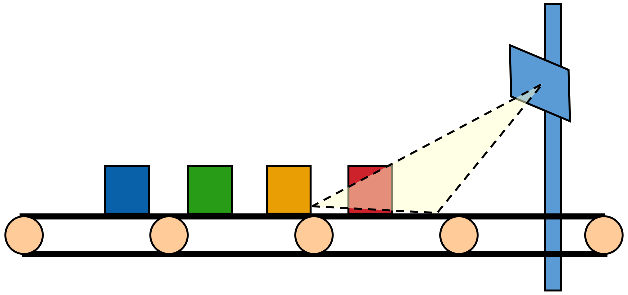
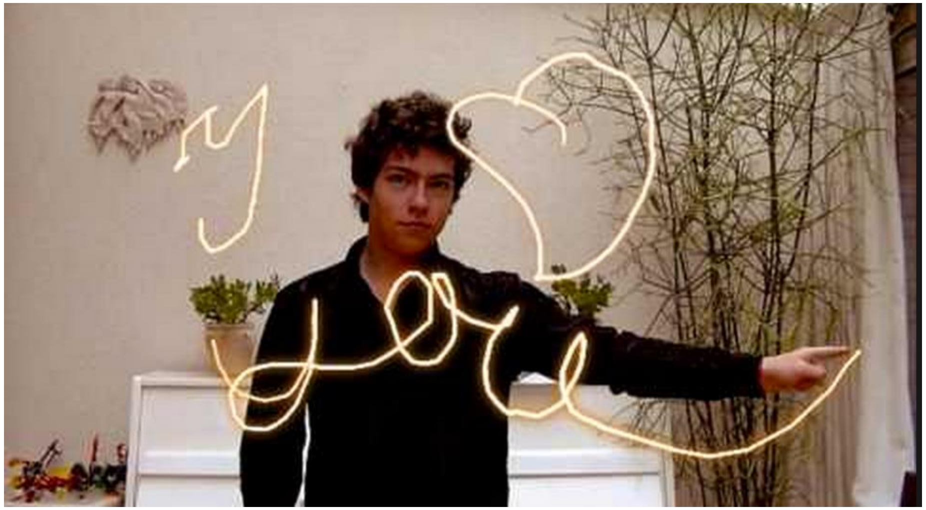


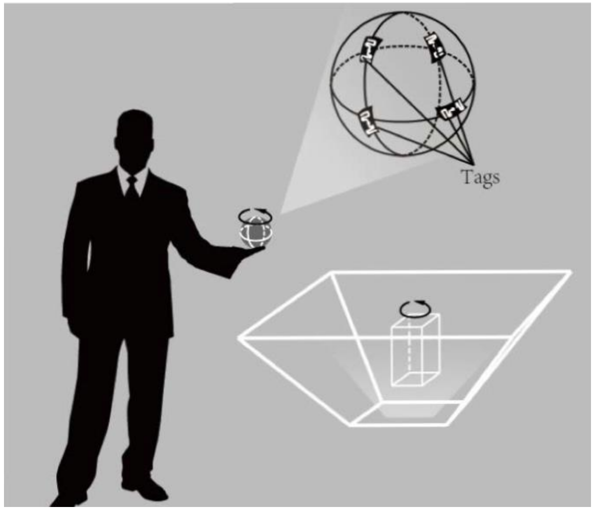
清華大學
Tsinghua University

Outline

1 Motivation

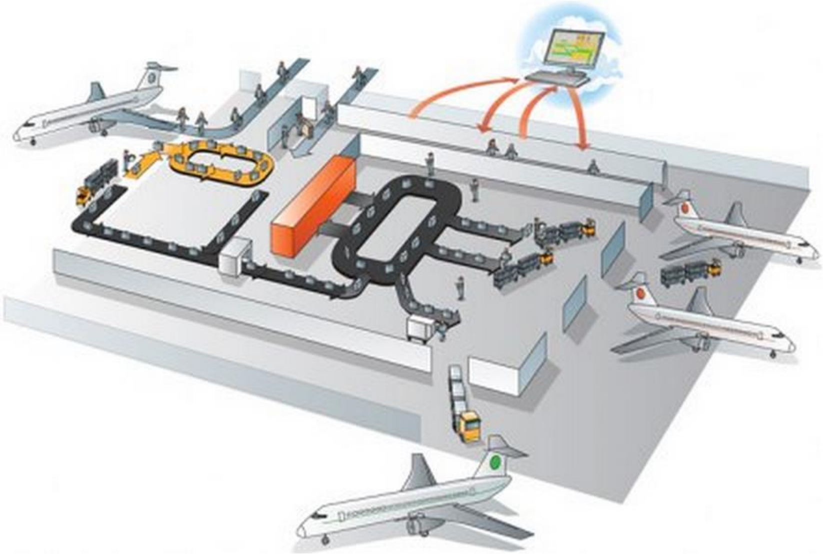
Imagine you can localize RFIDs to within 0.1cm to 1 cm!





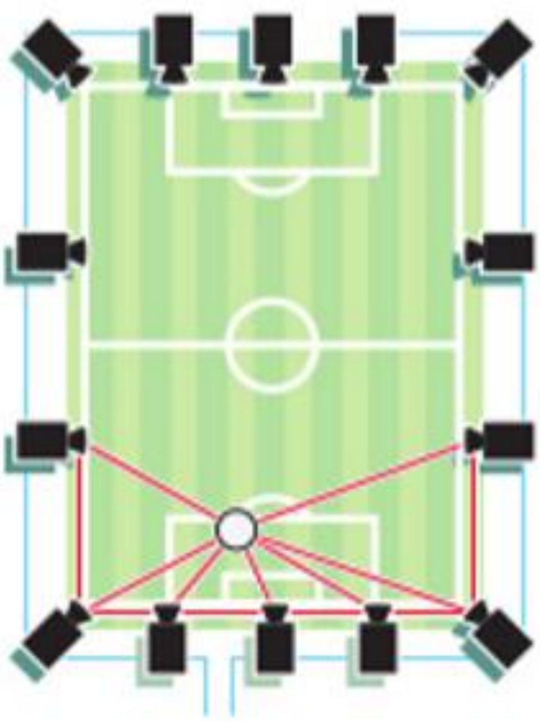
Human-computer interface

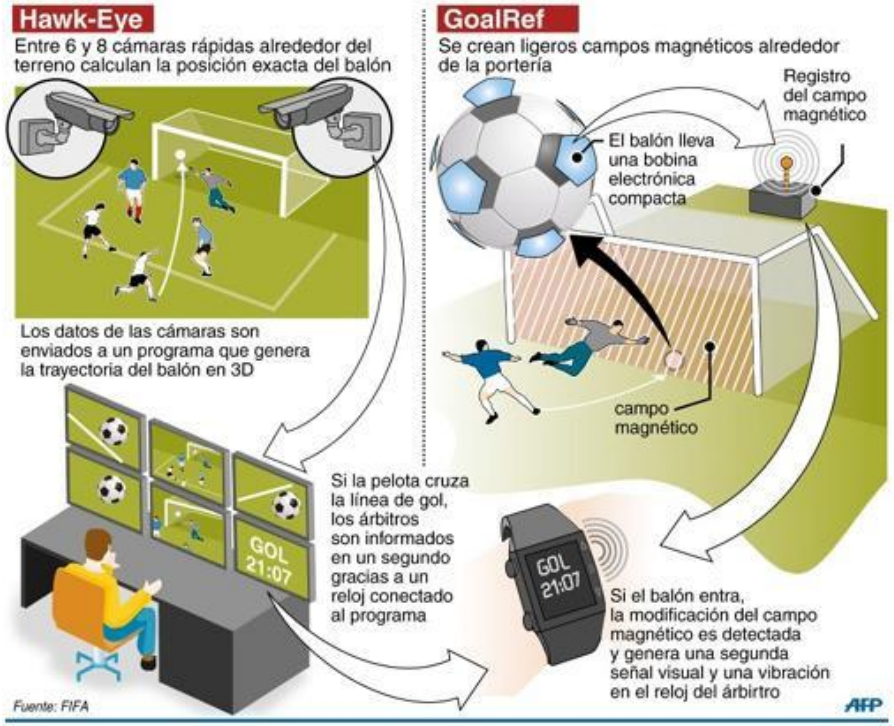
Imagine you can localize RFIDs to within 0.1cm to 1 cm!



Baggage sortation in airport

Imagine you can localize RFIDs to within 0.1cm to 1 cm!





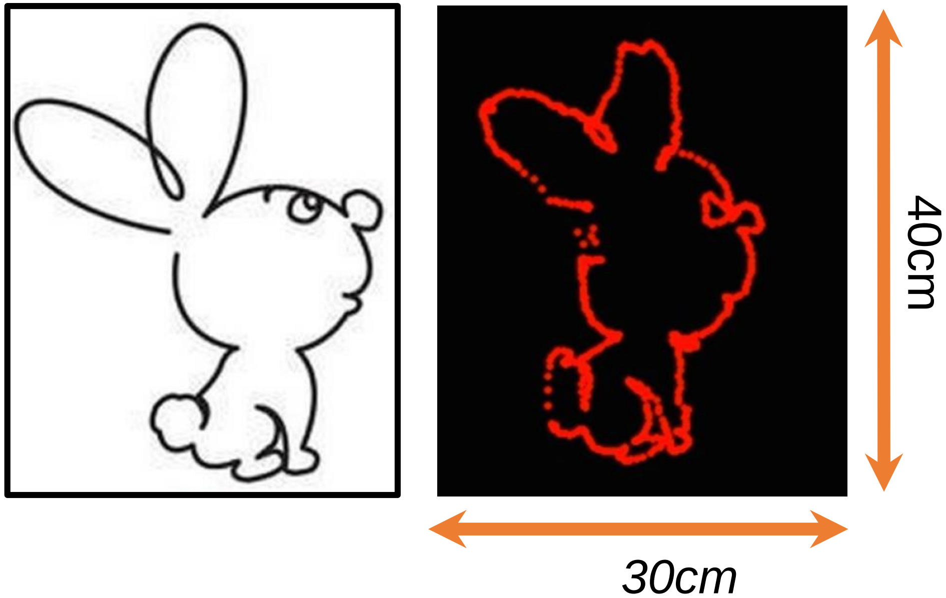
Goal-line technology

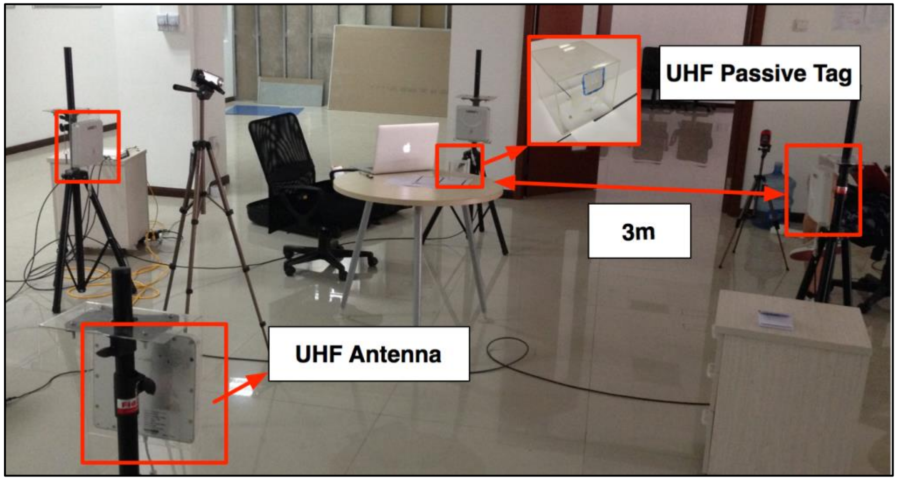
Demonstration

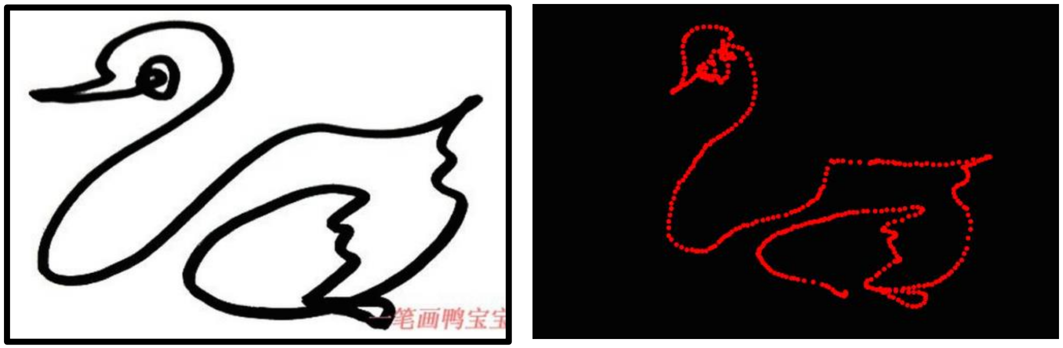
http://young.tagsys.org/tracking/tagoram/youtube

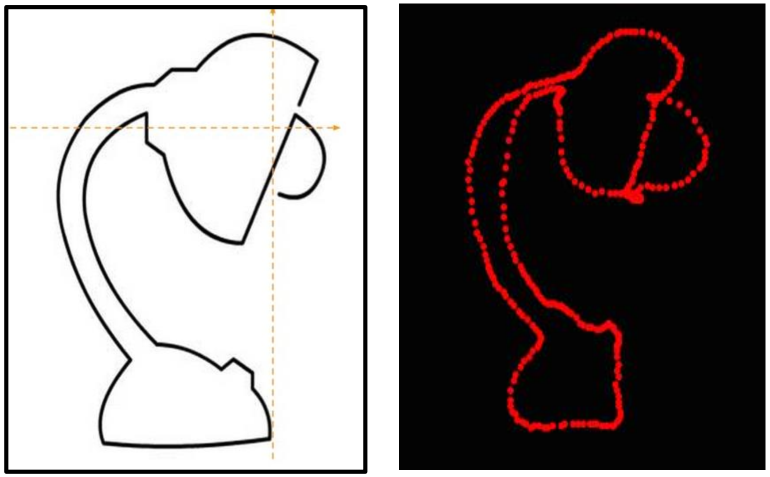
High-Precision RFID Tracking Using COTS Devices

Drawing in the Air

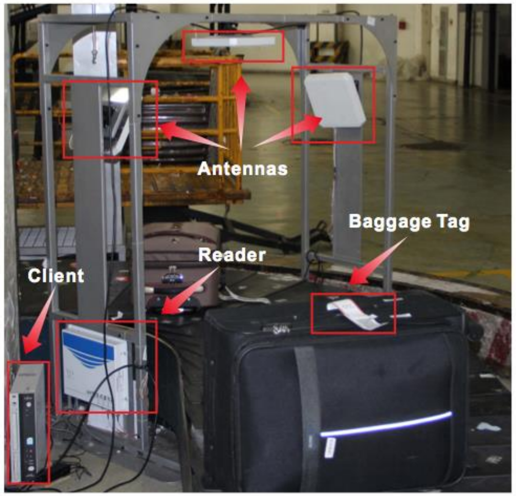








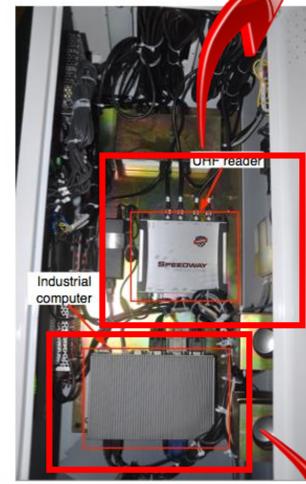
TrackPoint Deployed at Airports



(a) Version 1.0

(b) Version 2.0

Reader



(c) Internal structure

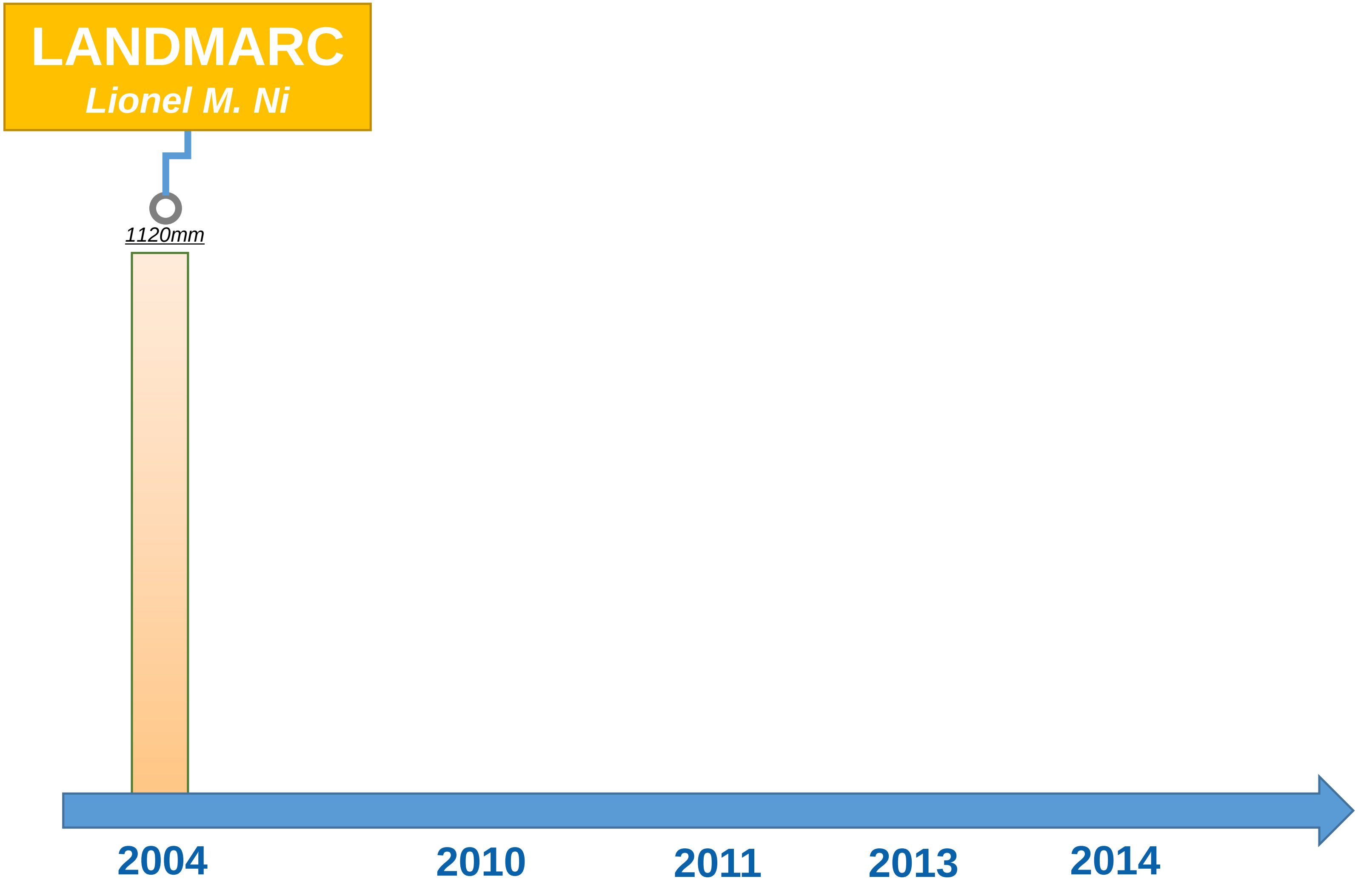
Industrial computer

(a) Two TrackPoints

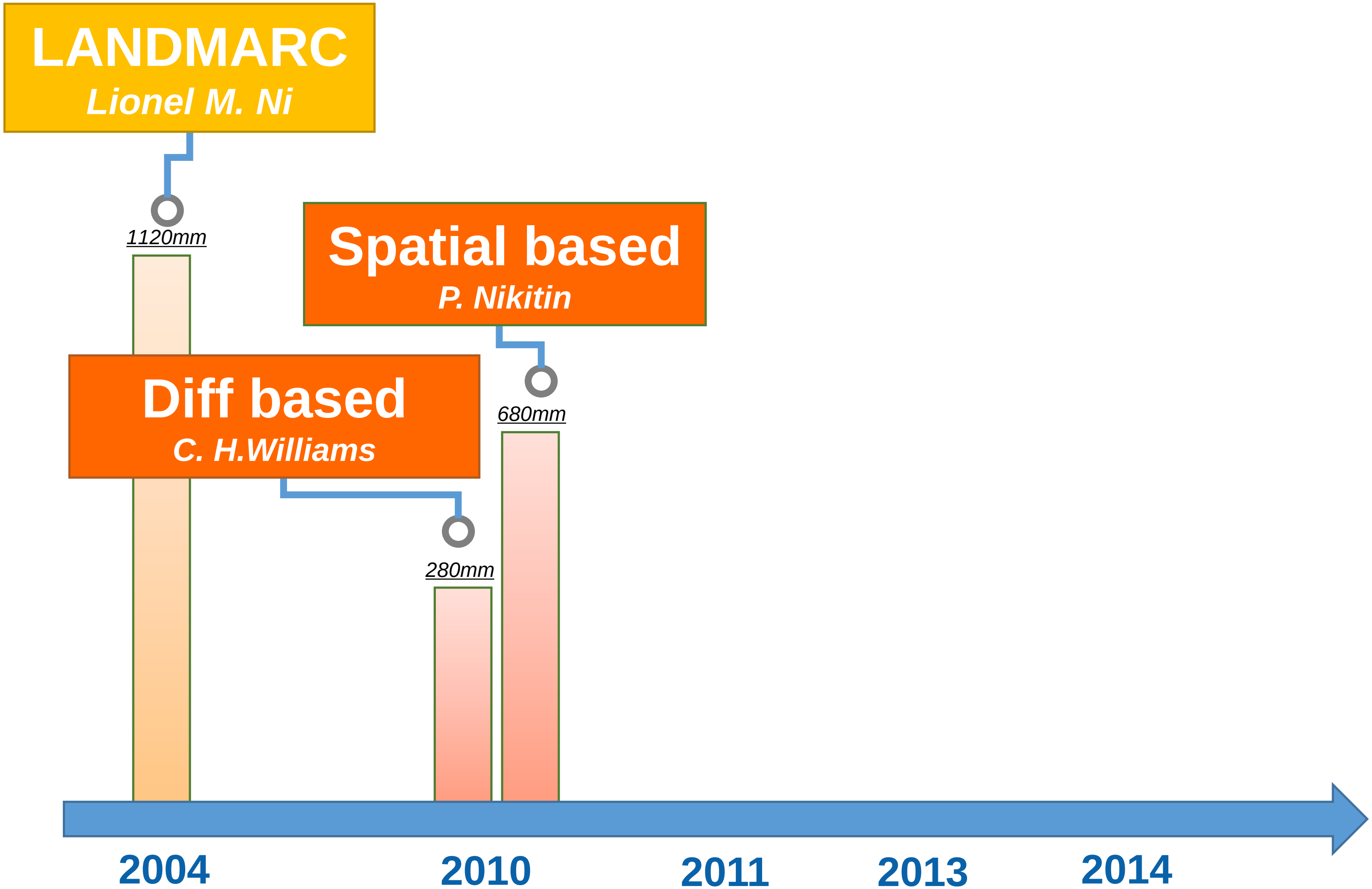
(b) Version 2.0

2 State-of-the-art

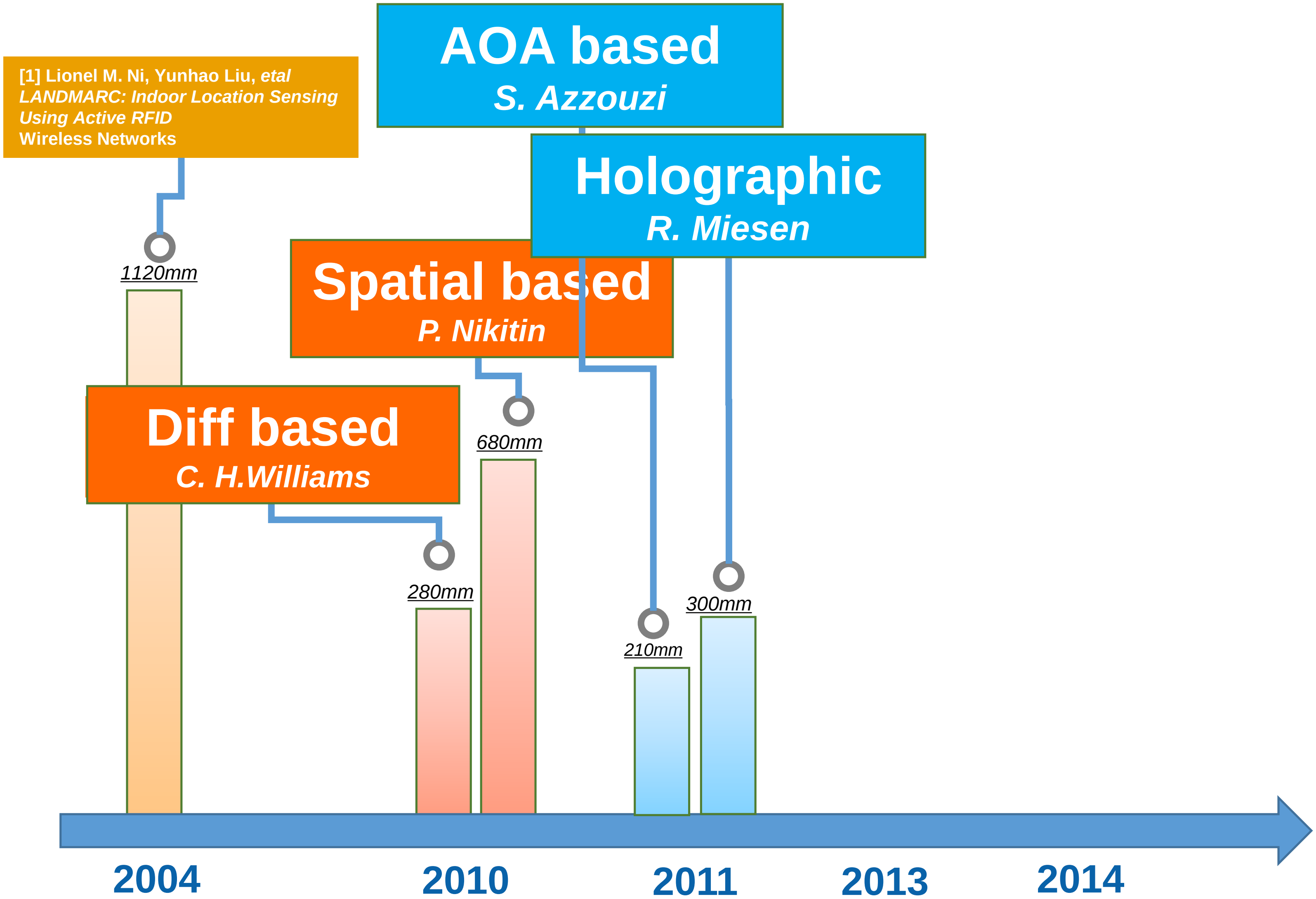
RFID Tracking & Localization
State-of-the-art



RFID Tracking & Localization
State-of-the-art

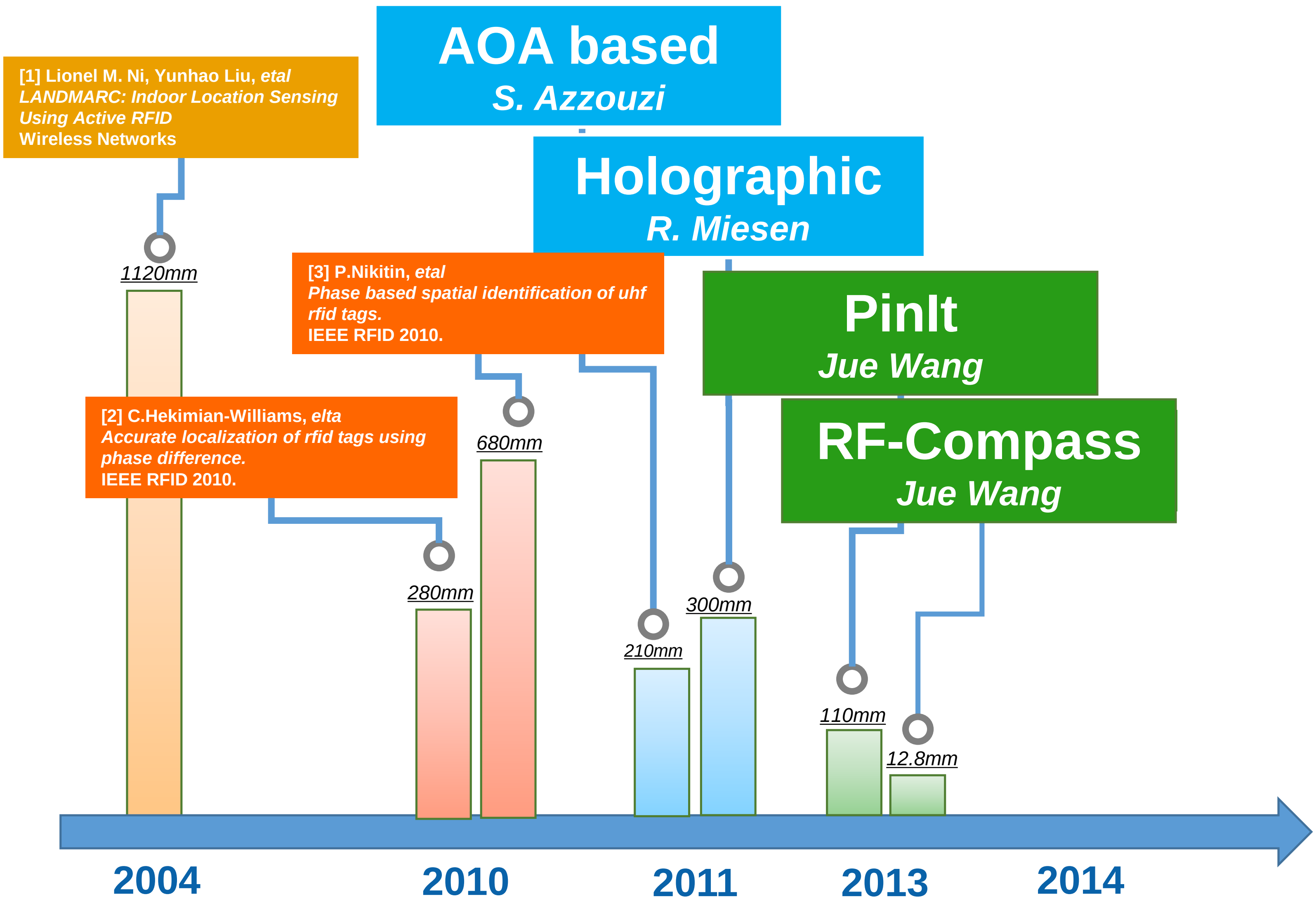


RFID Tracking & Localization
State-of-the-art

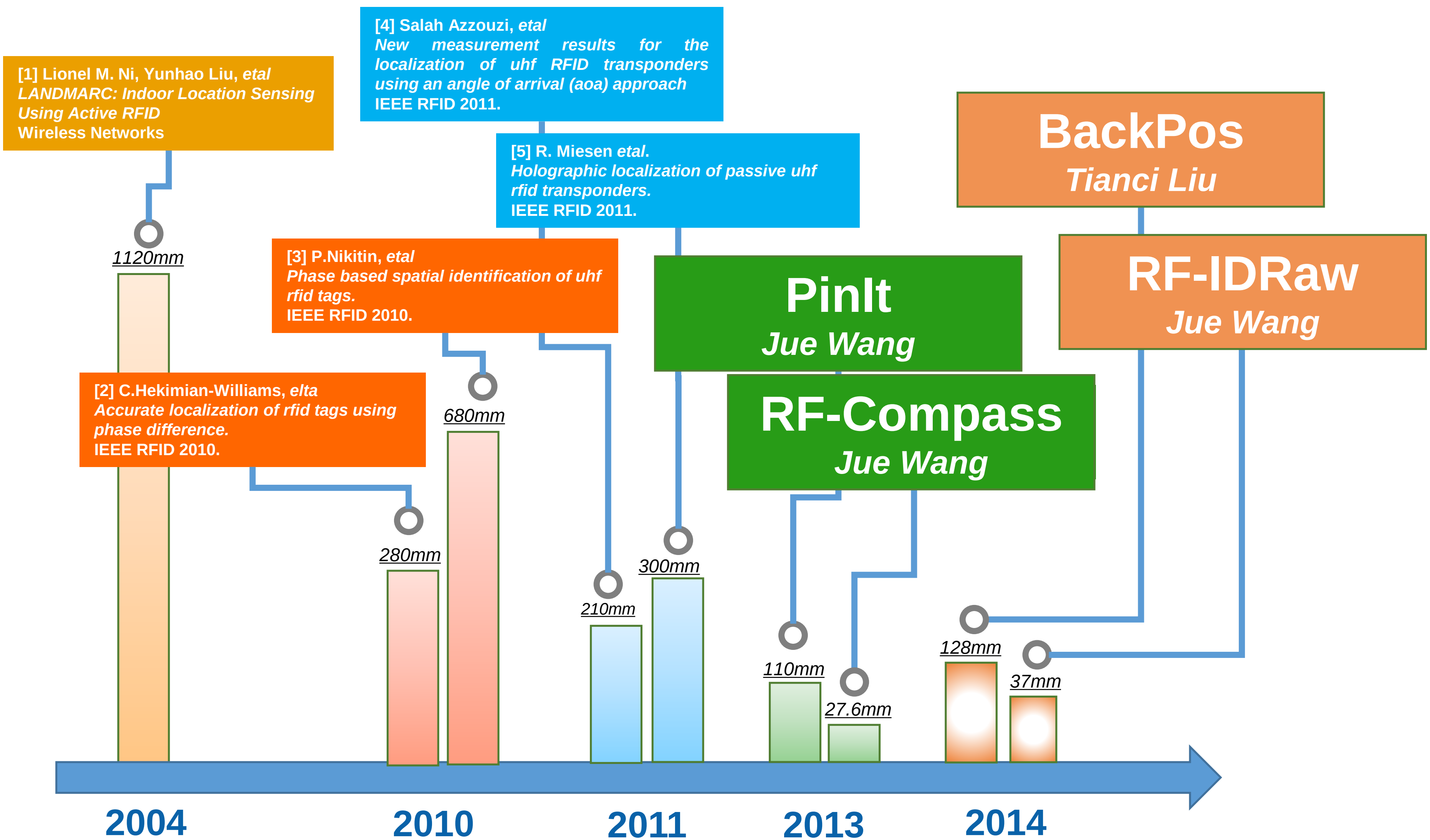


RFID Tracking & Localization

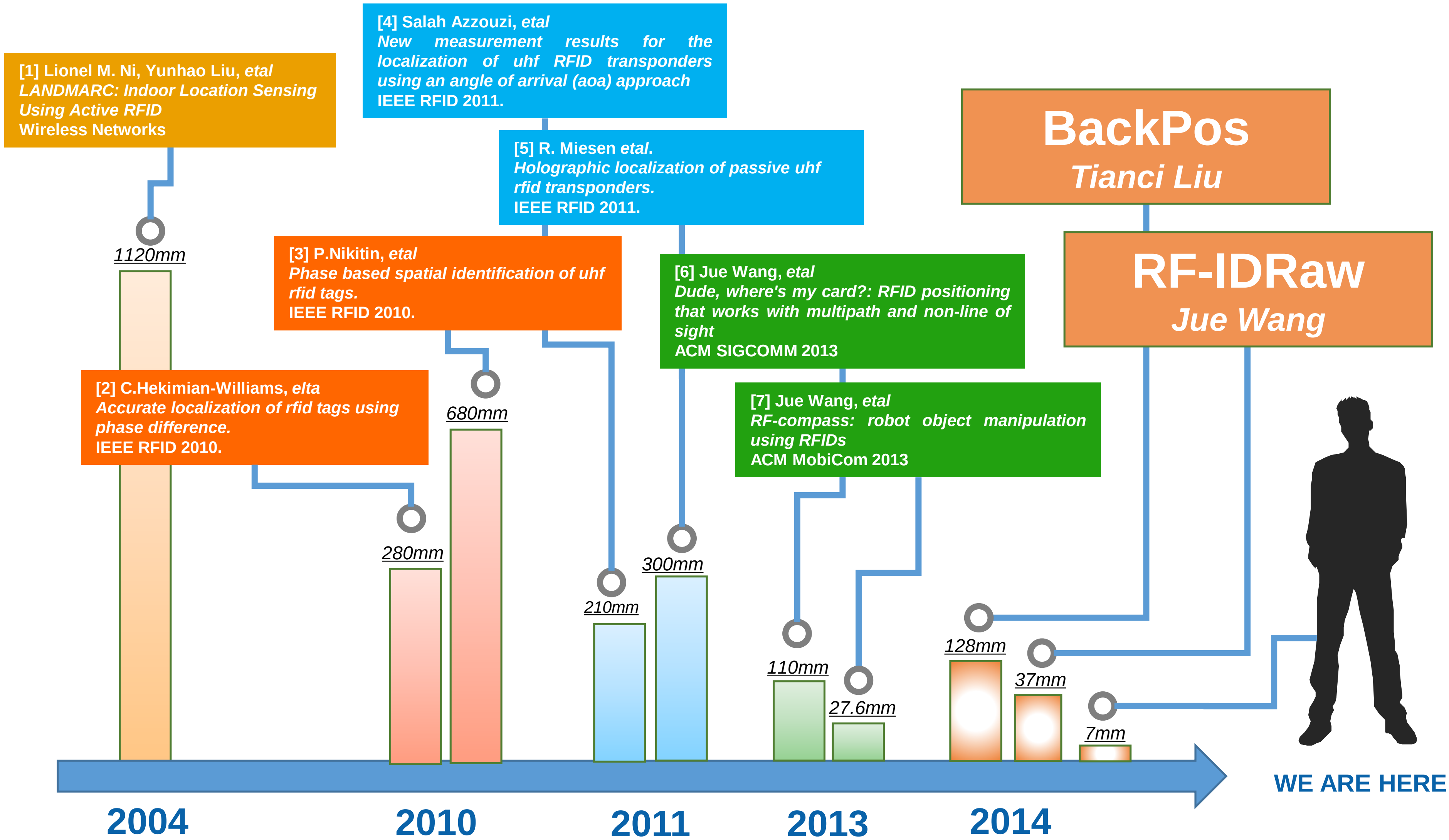
State-of-the-art



RFID Tracking & Localization
State-of-the-art

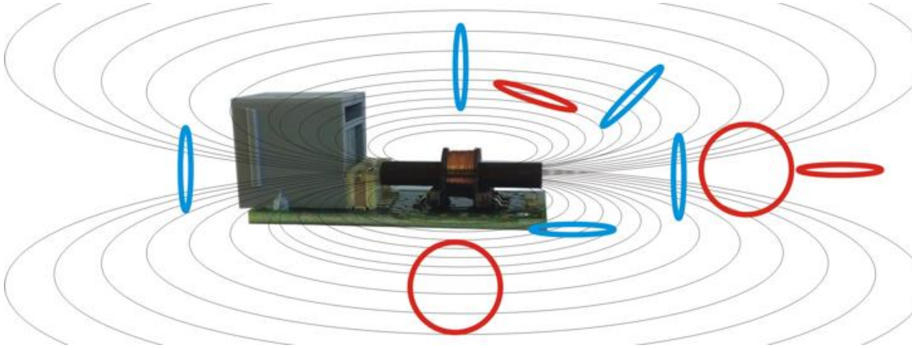


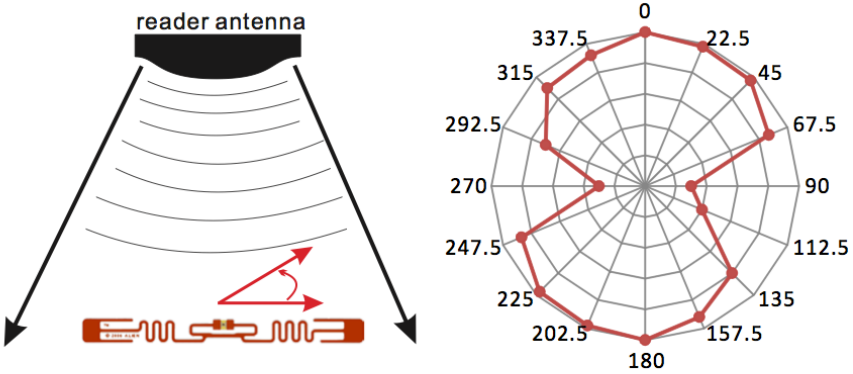
RFID Tracking & Localization
State-of-the-art



State-of-the-art Techniques

1 RSS based Methods



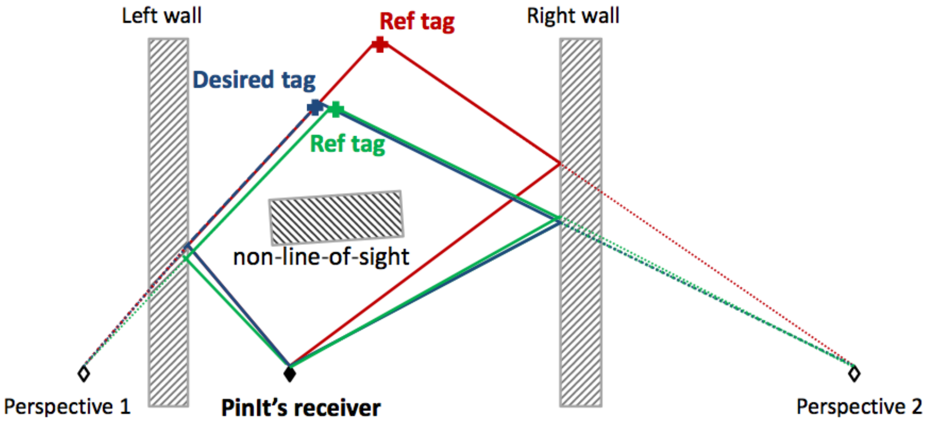


Orientation VS RSS

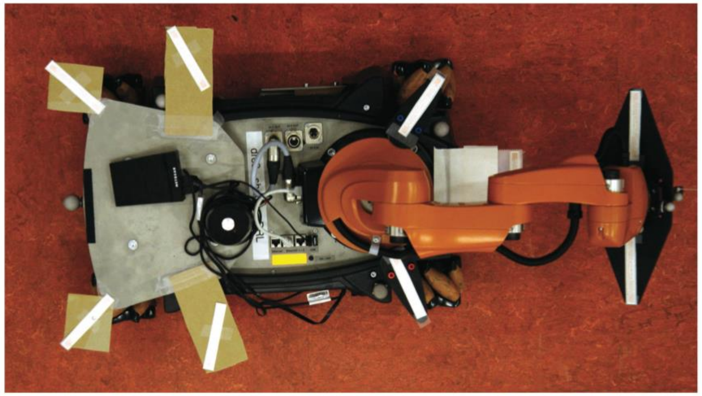
RSS is not a reliable location indicator especially for UHF tags

State-of-the-art Techniques

2 Phase based Methods



PinIt (SIGCOMM 2013)



RF-Compass (MobiCom 2013)

Needs to deploy dense reference tags

Summary of Challenges

- **Need mm-level localization accuracy achieved**
  - especially for mobile tags.
- **Small overhead, COTS devices**
  - infeasible for using many references for a tracking system spanning a long pipeline.
- **Fast-changing environment**
  - multipath reflection of RF signals
  - varied orientation of tags
  - Doppler effect

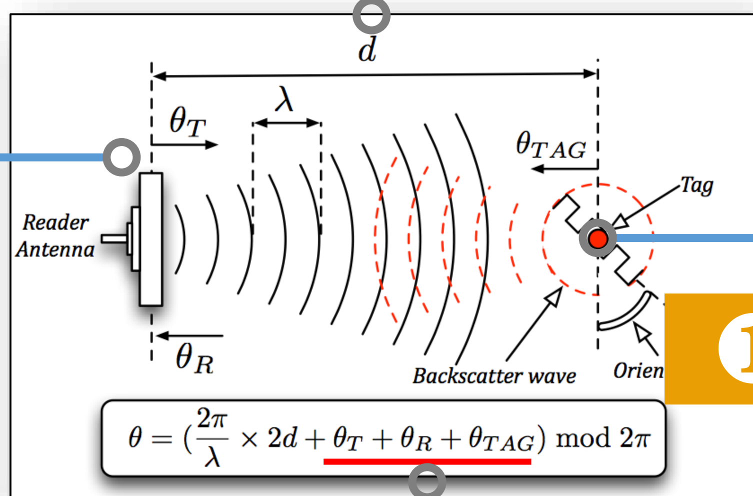
3 How Tagoram works?

Overview the basic idea

Backscatter Communication

❸ *Continuous wave*

❷ *Double distance*



❶ *Battery free*

❹ *Device diversity*

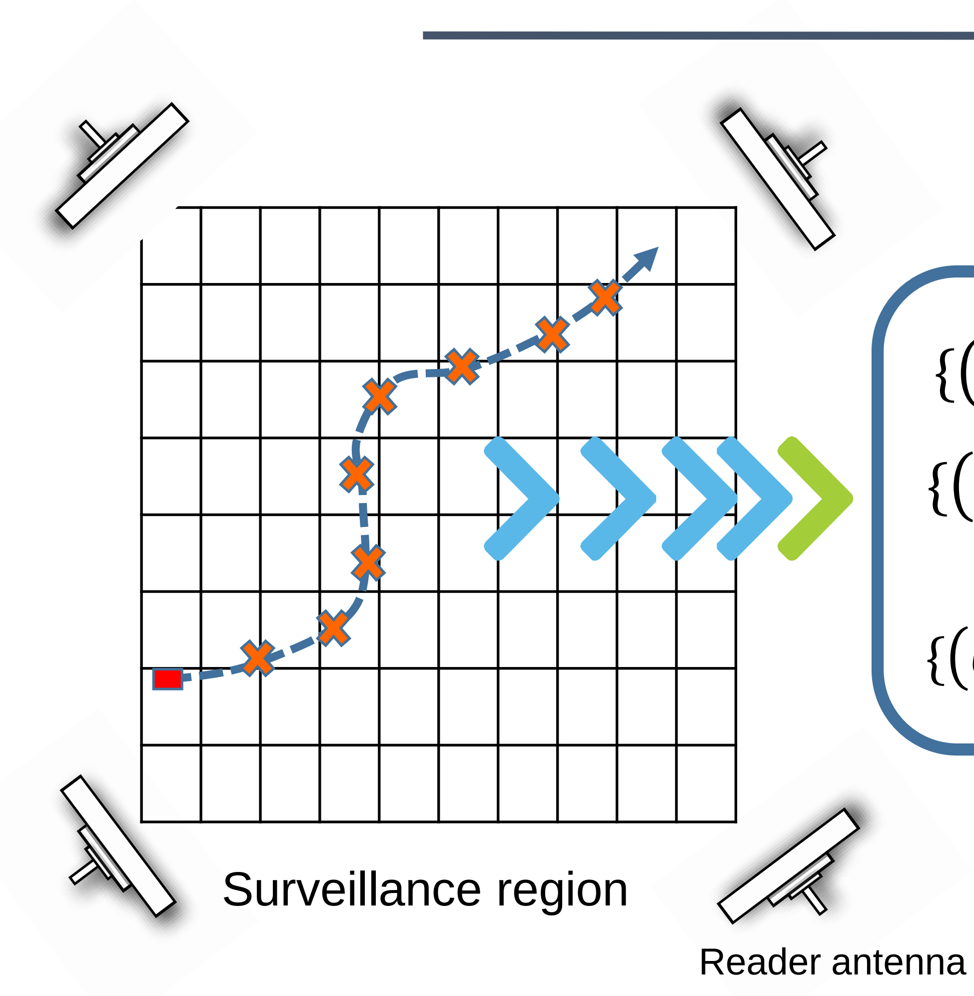
COTS RFID Reader

0.0015 radians (4096 bits)

≈ $0.038mm$ accuracy

Impinj Reader

Problem definition



$$M \times N$$

$$\{(\theta_{1,1}, t_{1,1}), (\theta_{1,2}, t_{1,2}) \cdots, (\theta_{1,N}, t_{1,N})\}$$
$$\{(\theta_{2,1}, t_{2,1}), (\theta_{2,2}, t_{2,2}) \cdots, (\theta_{2,N}, t_{2,N})\}$$
$$\vdots \qquad \vdots \qquad \vdots$$
$$\{(\theta_{M,1}, t_{M,1}), (\theta_{M,2}, t_{M,2}) \cdots, (\theta_{M,N}, t_{M,N})\}$$

Utilizing antennas' locations, sampled phase values and timestamps to find out the tag's trajectory $f(t)$?

Tagoram

Case 1. Controllable Case

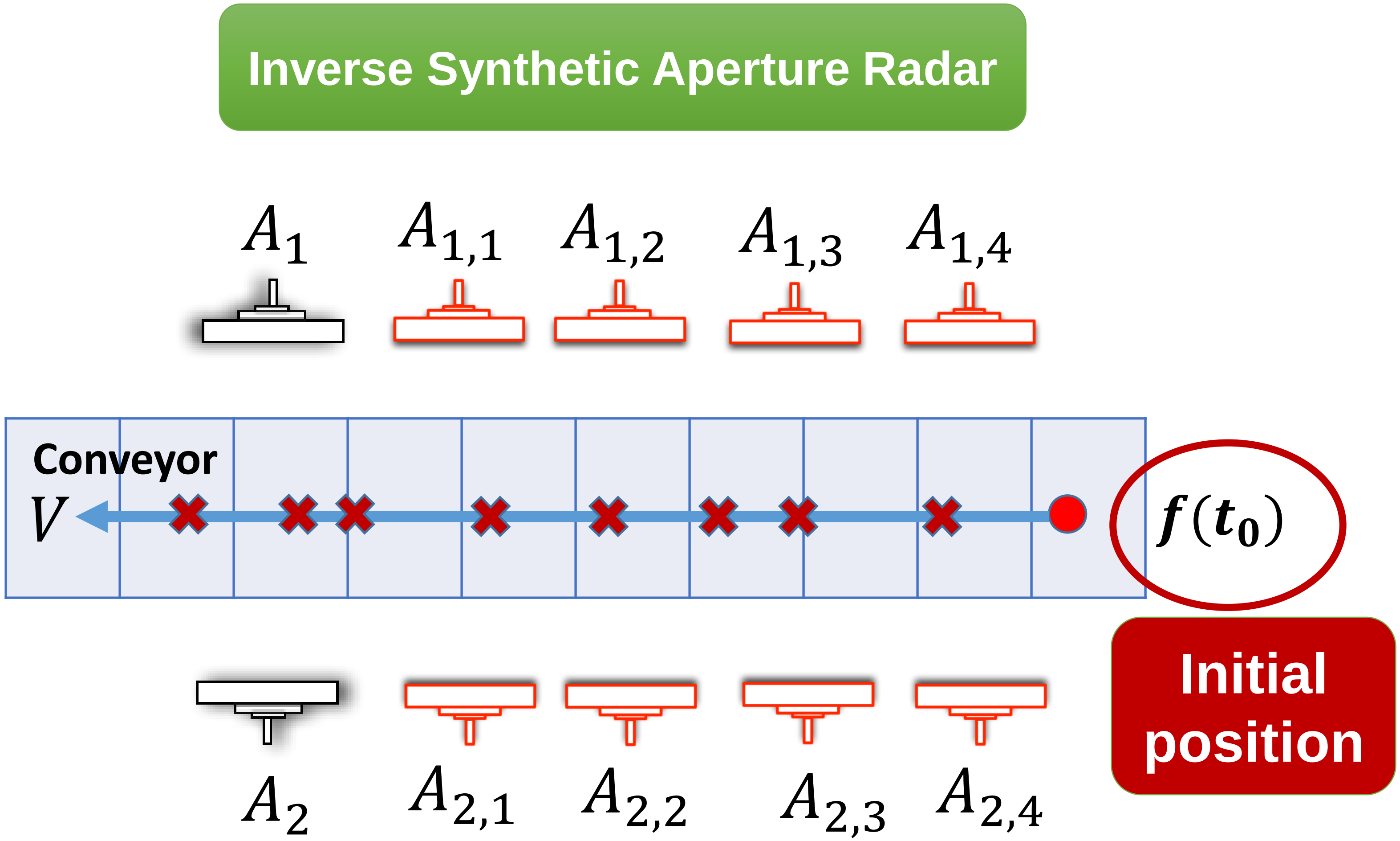
Case 2. Uncontrollable Case

4 Movement with Known Track

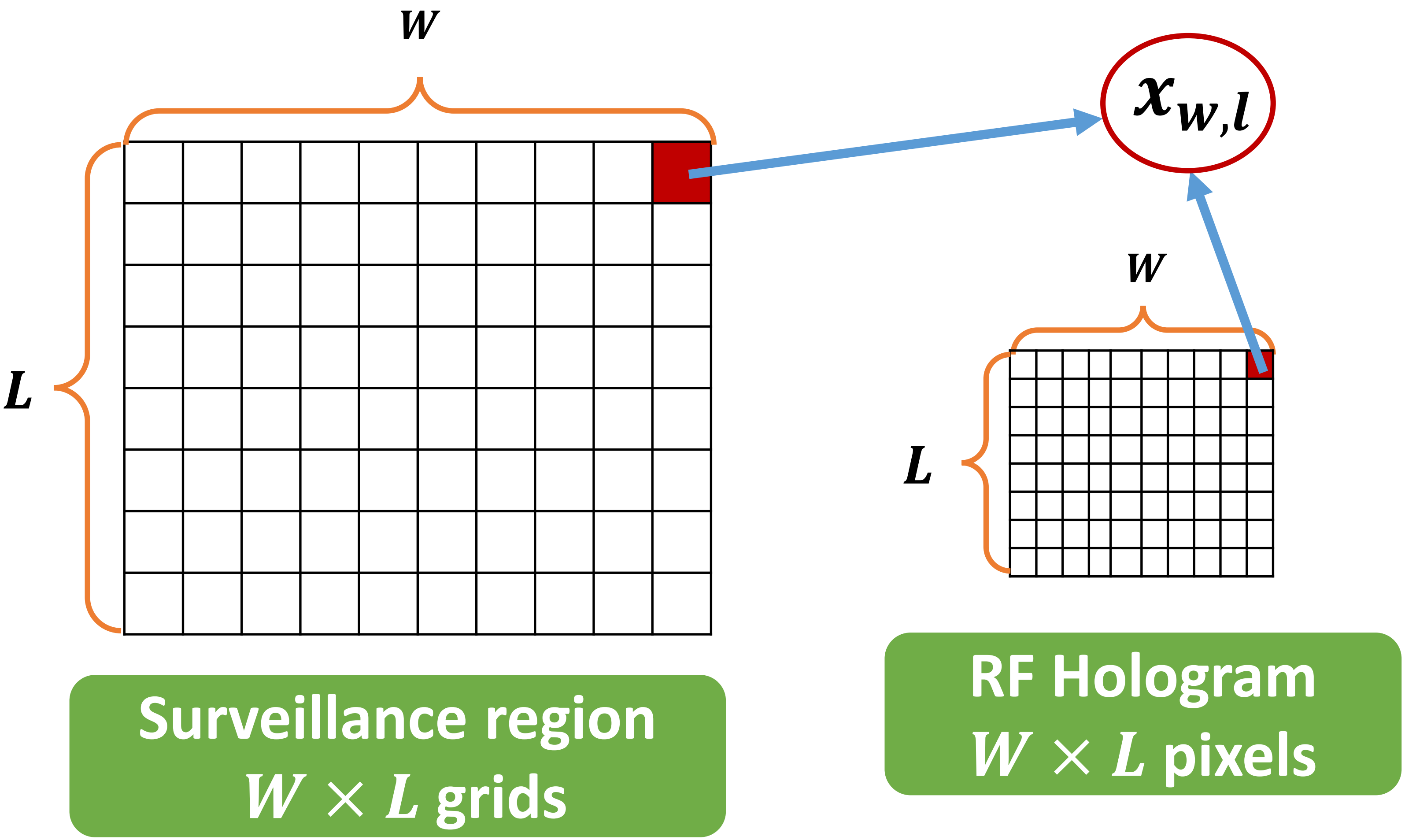
Controllable case

Our goal is to find the tag's trajectory with a known track.

Virtual Antenna Matrix



RF Hologram



W
L
$x_{w,l}$
W
L
Surveillance region
$W \times L$ grids
RF Hologram
$W \times L$ pixels

The key is

How to define the likelihood?

RF Hologram

Naïve Hologram

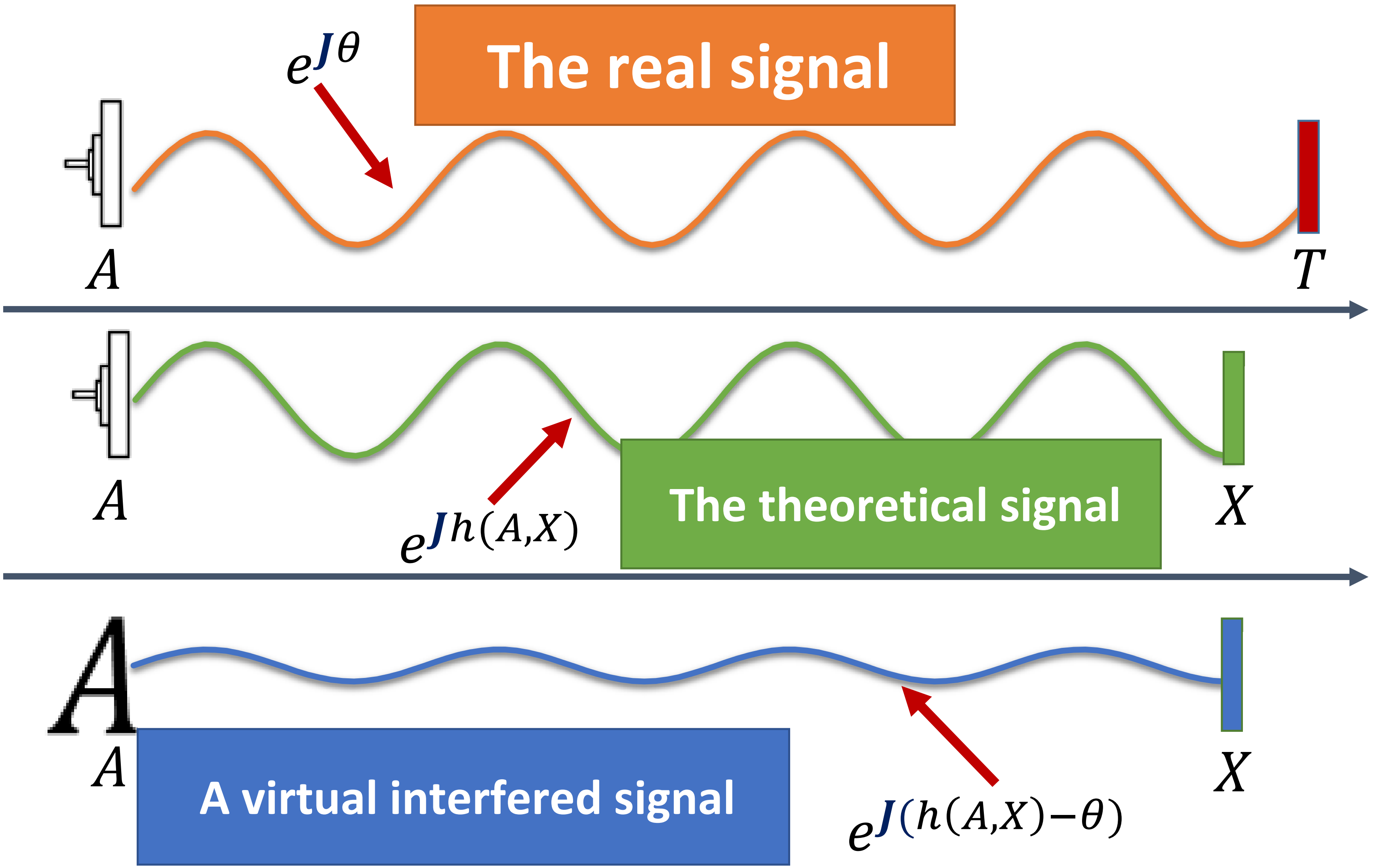
Augmented Hologram

Thermal noise

Device diversity

Differential Augmented Hologram

Naïve Hologram



Naïve Hologram

Sum of all signals

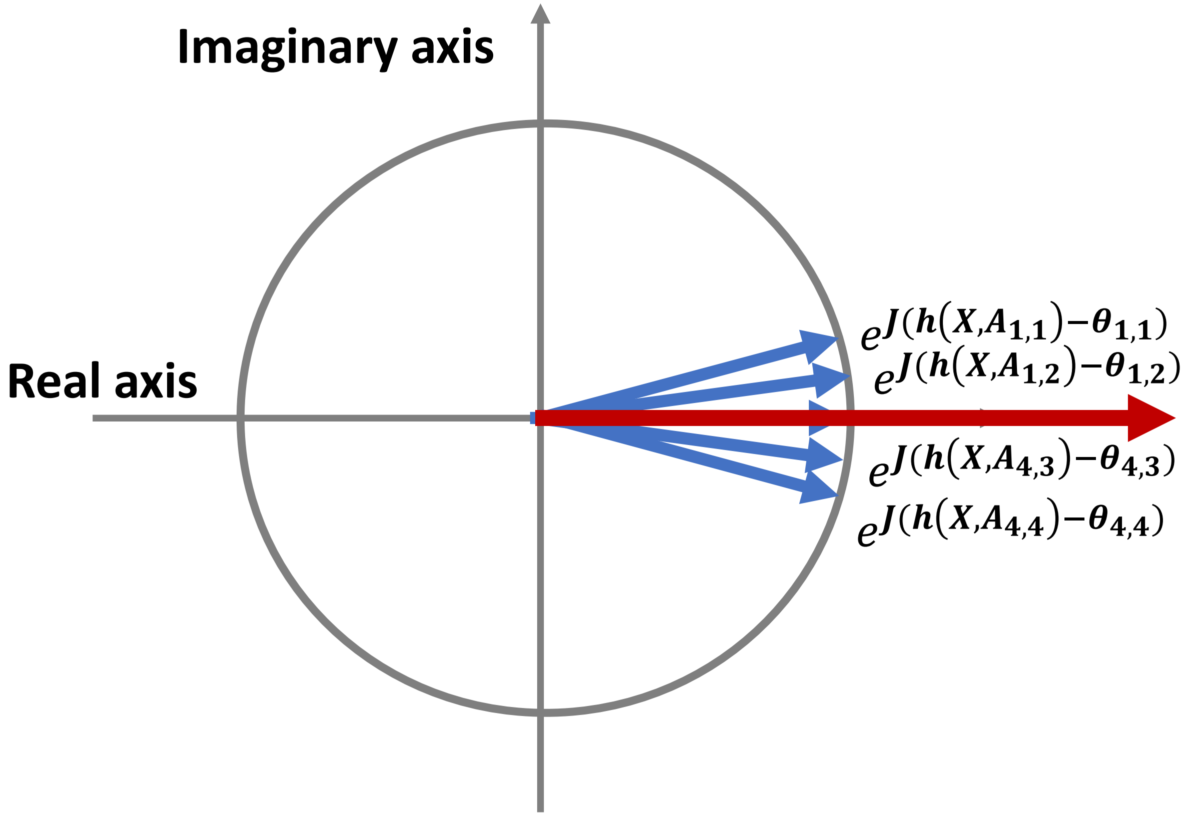
DEFINIT). *The naive holo-gram is an image in which the pixel value $x_{w,l}$, indicating the likelihood that the corresponding grid $X_{w,i}$ is the initial position, is calculated by*

$$x_{w,l} = \left| \sum_{m=1}^{M} \sum_{n=1}^{N} S(X_{w,l}, A_{m,n}, \theta_{m,n}) \right| \qquad (9)$$

where $S(X, A, \theta) = e^{\mathbf{J}(h(X,A)-\theta)}$. The term $\mathbf{J}$ denotes the imaginary number and the term $e^{\mathbf{J}\theta}$ represents a complex exponential

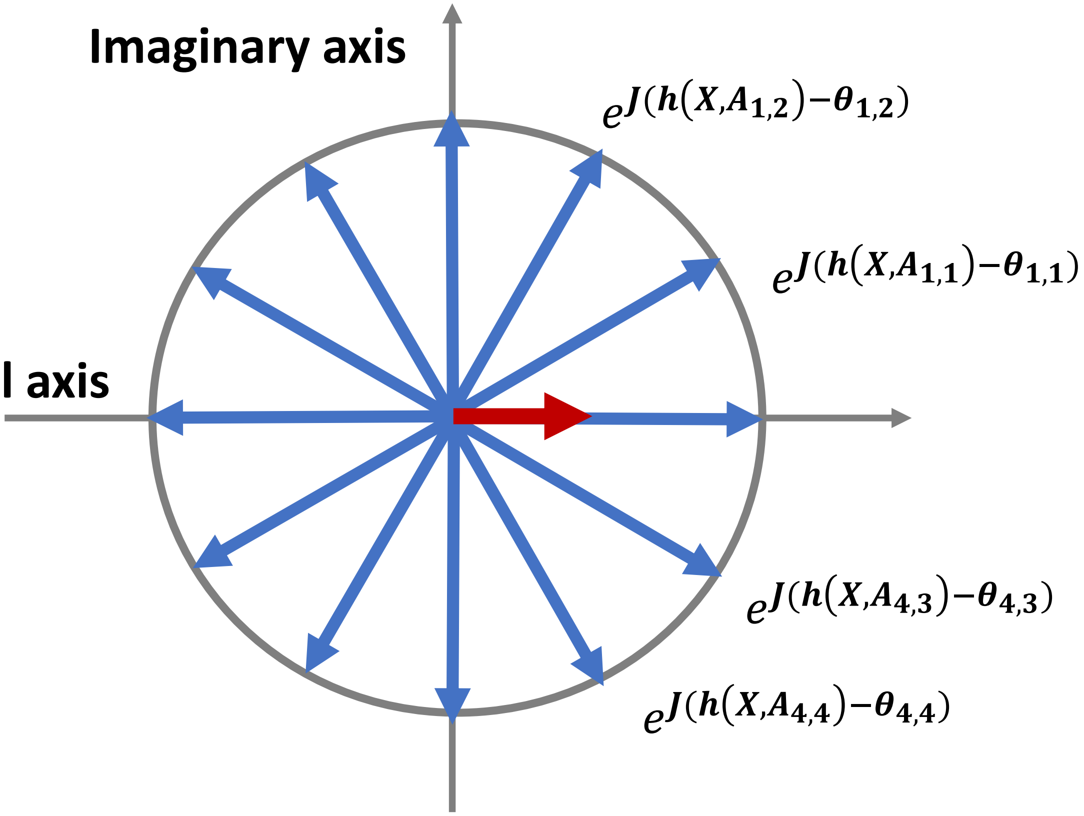
Virtual interfered signal

Naïve Hologram



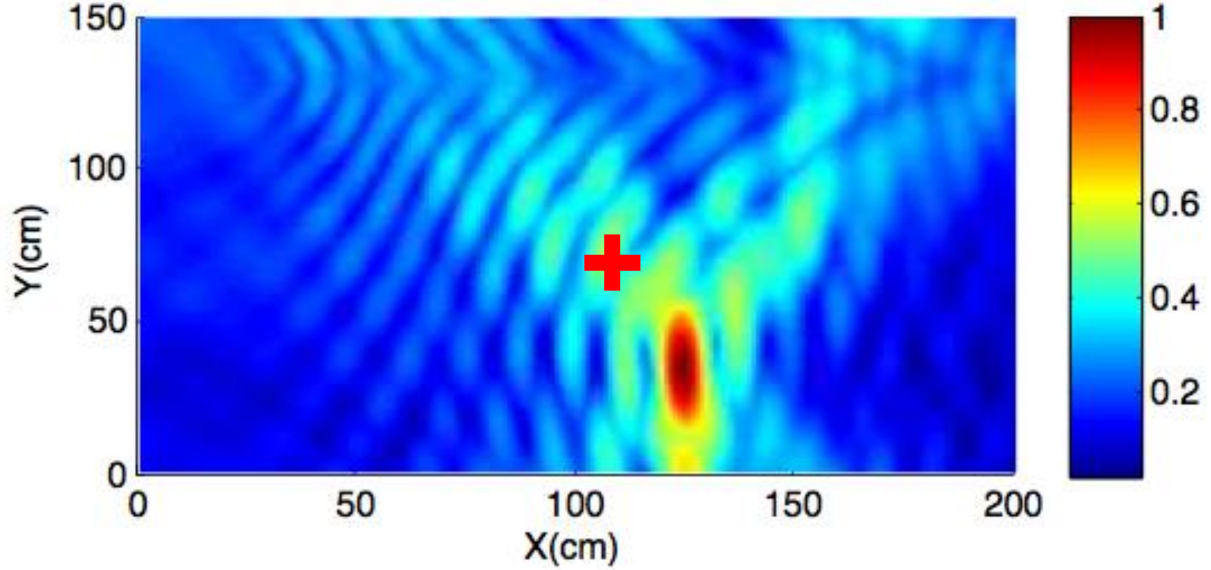
If X is the initial location, the waves add up constructively.

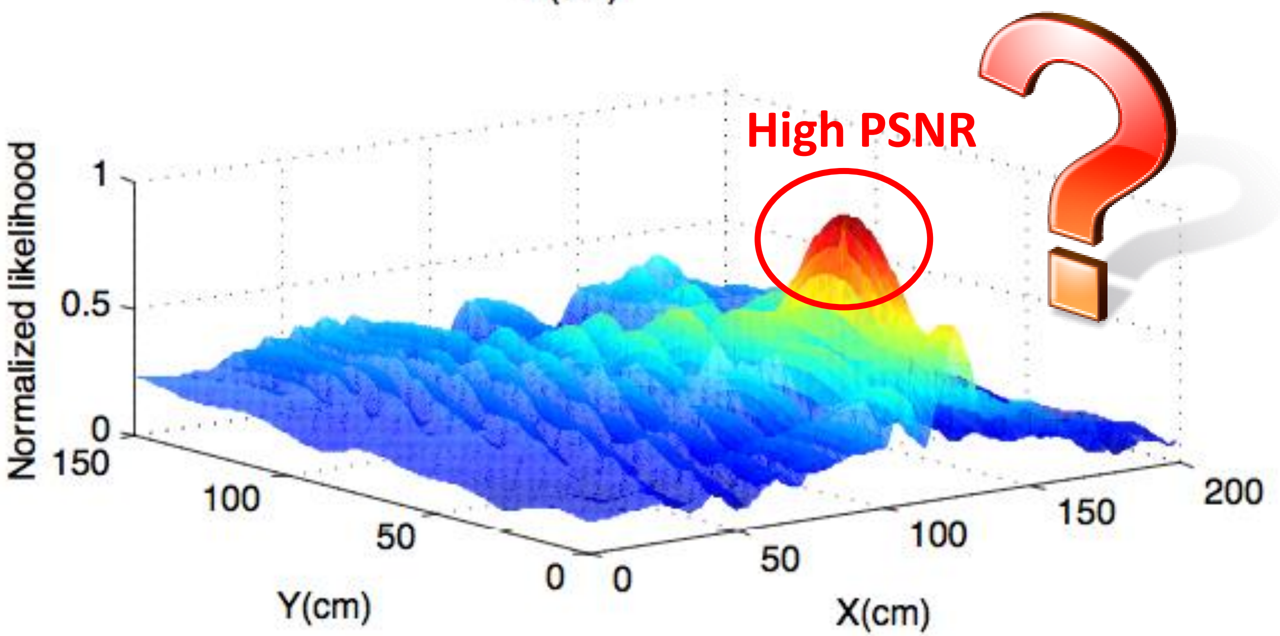
Naïve Hologram



If X is not the initial location, the waves canceled out.

Naïve Hologram





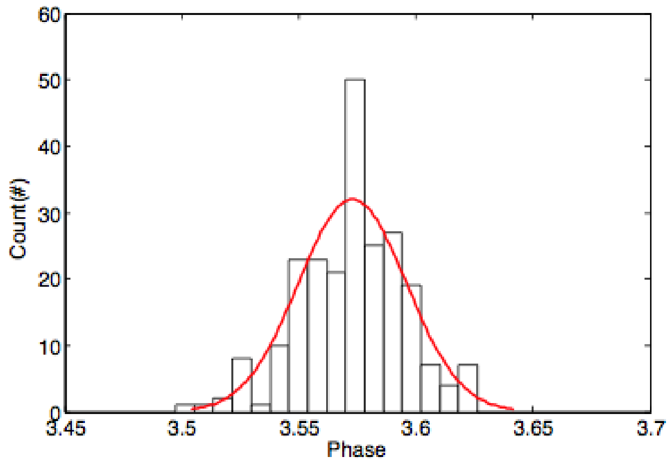
Influence from Thermal Noise

100 tags

0°~40°

$920 \sim 926\ MHz$

$-70 \sim -30dbm$



Experiment	Observations
Modeling	CDF

$$\theta \sim \mathcal{N}(\mu, \sigma)$$

$$F(\theta; \mu, \sigma)$$

varying with d

$\sigma = 0.1$

How to deal with thermal noise?

Augmented Hologram

Augmented Hologram

A probabilistic weight

$(h(X, A) - \theta) \sim \mathcal{N}(0, 0.1)$

DEFINITION 2 (AH). *The augmented hologram is an image in which the pixel value $x_{w,l}$ is*

$$x_{w,l} = \left| \sum_{m=1}^{M} \sum_{n=1}^{N} \|S(X_{w,l}, A_{m,n}, \theta_{m,n})\| S(X_{w,l}, A_{m,n}, \theta_{m,n}) \right| \quad (10)$$

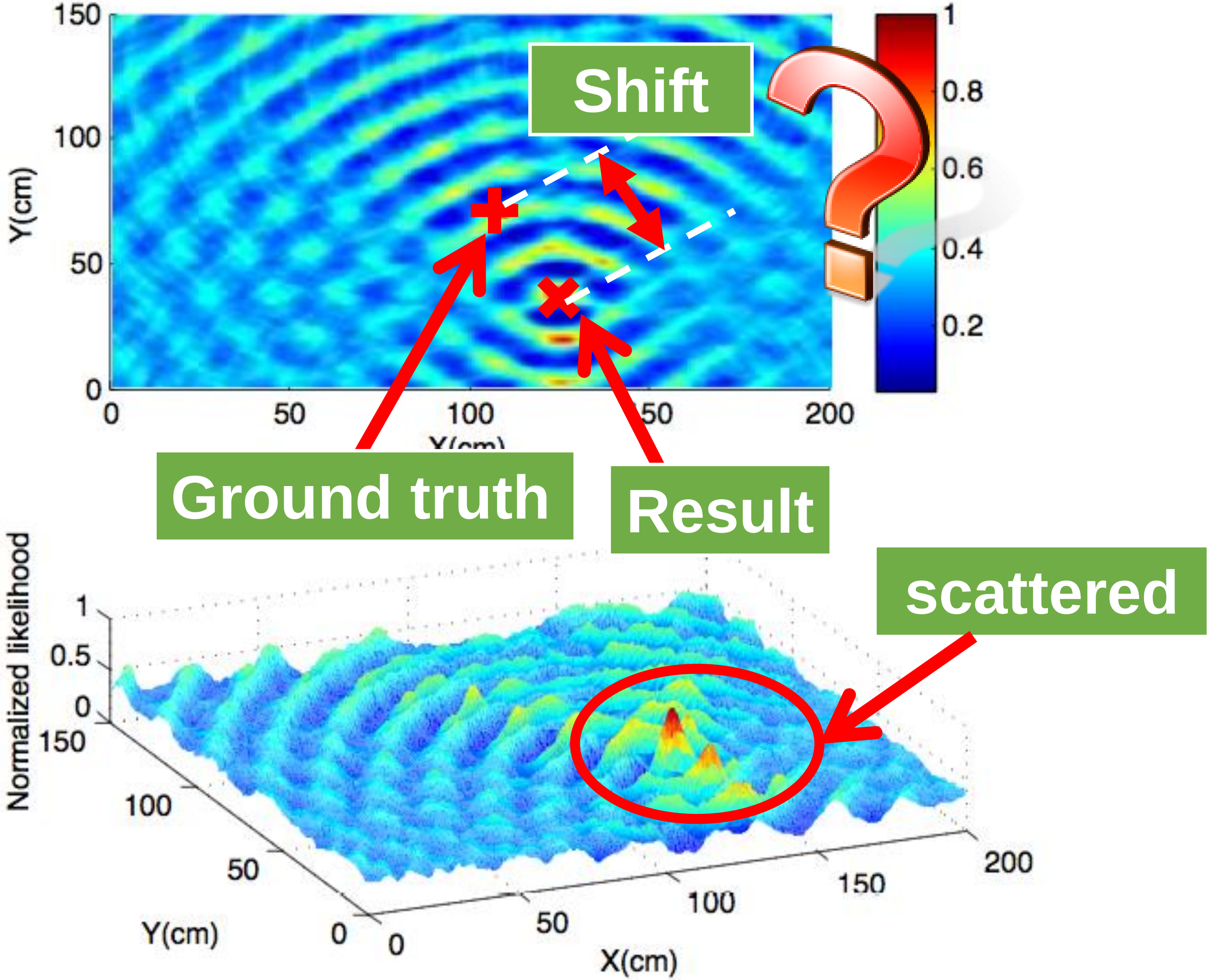
where

$$\begin{cases} \|S(X, A, \theta)\| = 2 \times F(|h(X, A) - \theta|; 0, 0.1) \\ F(x; \mu, \sigma) = \dfrac{1}{\sigma\sqrt{2\pi}} \displaystyle\int_x^{\infty} \exp\left(-\dfrac{(t-\mu)^2}{2\sigma^2}\right) dt \end{cases}$$

and $F(x; \mu, \sigma)$ is the cumulative probability function of Gaussian distribution $\mathcal{N}(\mu, \sigma)$.

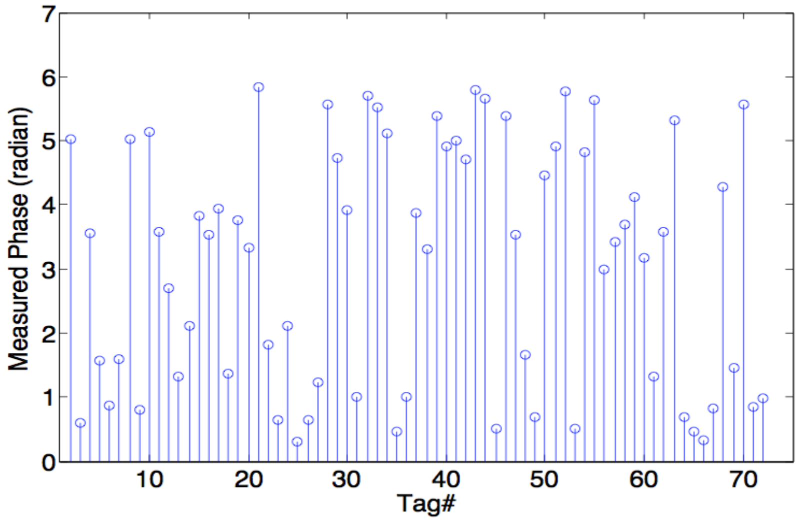
Probability of $T \to A$

Augmented Hologram



Influence from Tag Diversity

70 tags · ***100* times** · **At same position**



Experiment	Observations
Modeling	Random test

$$\begin{cases} \theta = \left(\frac{2\pi}{\lambda} \times 2d + c\right) \bmod 2\pi \\ c = \theta_T + \theta_R + \theta_{TAG} \end{cases}$$

Tag diversity

Pass *KS-test* to be verified over a *uniform distribution* with 0.5 significant level.

How to eliminate tag diversity?

Differential Augmented Hologram

Differential Augmented Hologram

DEFINITION 3 (DAH). *The differential augmented hologram is an image in which the pixel value is calculated by*

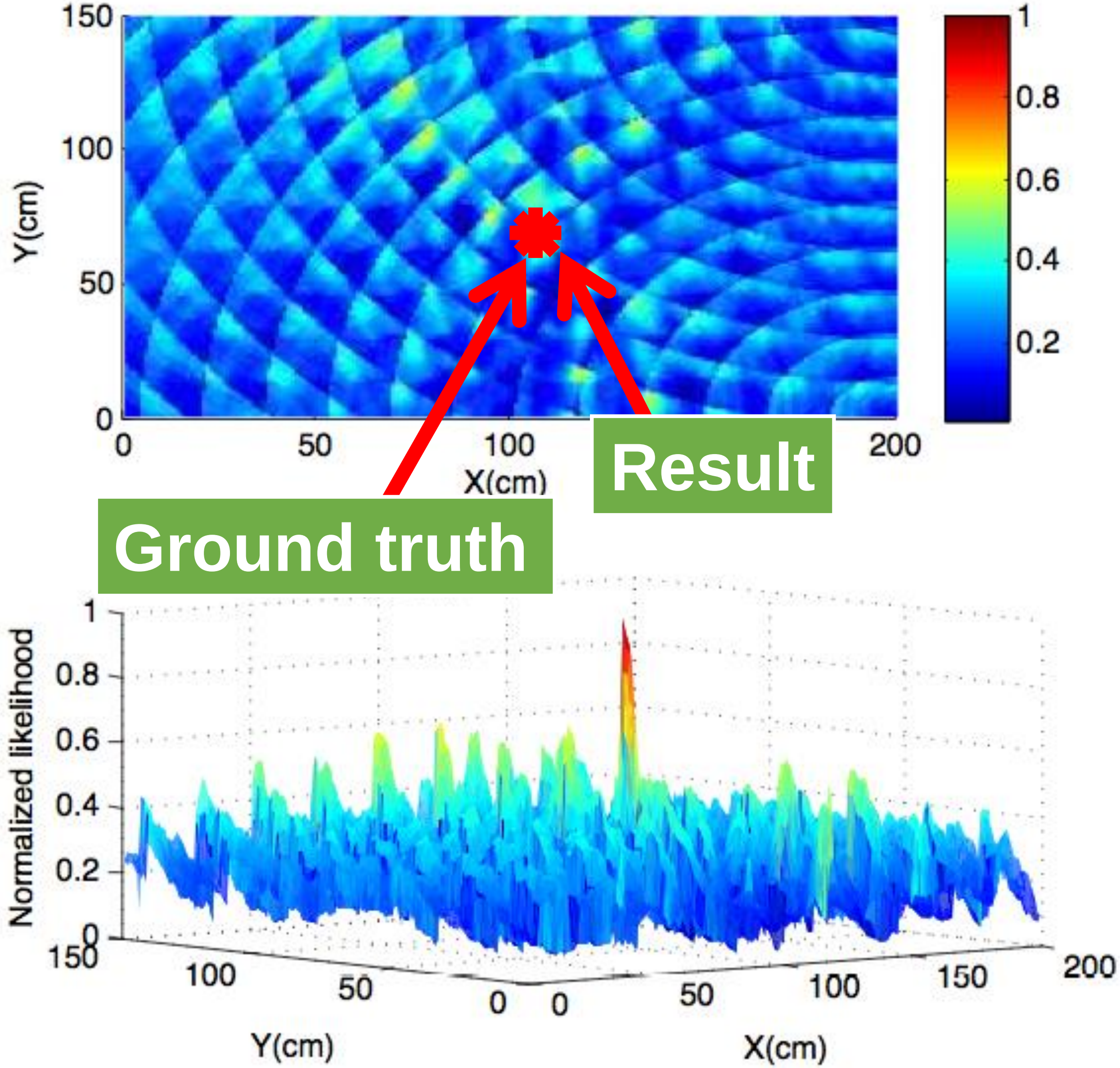
$$x_{w,l} = \left| \sum_{m=1}^{M} \sum_{n=1}^{N} \|\mathbb{S}(X_{w,l}, A_{m,n}, \theta_{m,n})\| \mathbb{S}(X_{w,l}, A_{m,n}, \theta_{m,n}) \right| \quad (11)$$

where

$$\begin{cases} \mathbb{S}(X_{w,l}, A_{m,n}, \theta_{m,n}) = e^{\mathbf{J}\theta_{dif}} \\ \|\mathbb{S}(X_{w,l}, A_{m,n}, \theta_{m,n})\| = 2 \times F(|\theta_{dif}|; 0, 0.1 \times \sqrt{2}) \\ \theta_{dif} = (h(X_{w,l}, A_{m,n}) - \theta_{m,n}) - (h(X_{w,l}, A_{m,1}) - \theta_{m,1})) \end{cases}$$

Using the difference of phase values

Differential Augmented Hologram



5 Movement with Unknown Track

Uncontrollable case

Overview

1. Estimating Speeds,
   Fitting tag’s trajectory
2. Selecting the optimal trajectory

6 Implementation & Evaluation

Purely based on COTS devices

Hardware & Software Introduction

Reader

ImpinJ R420 reader.

4 directional antennas

Tag

Alien 2 × 2 Inlay

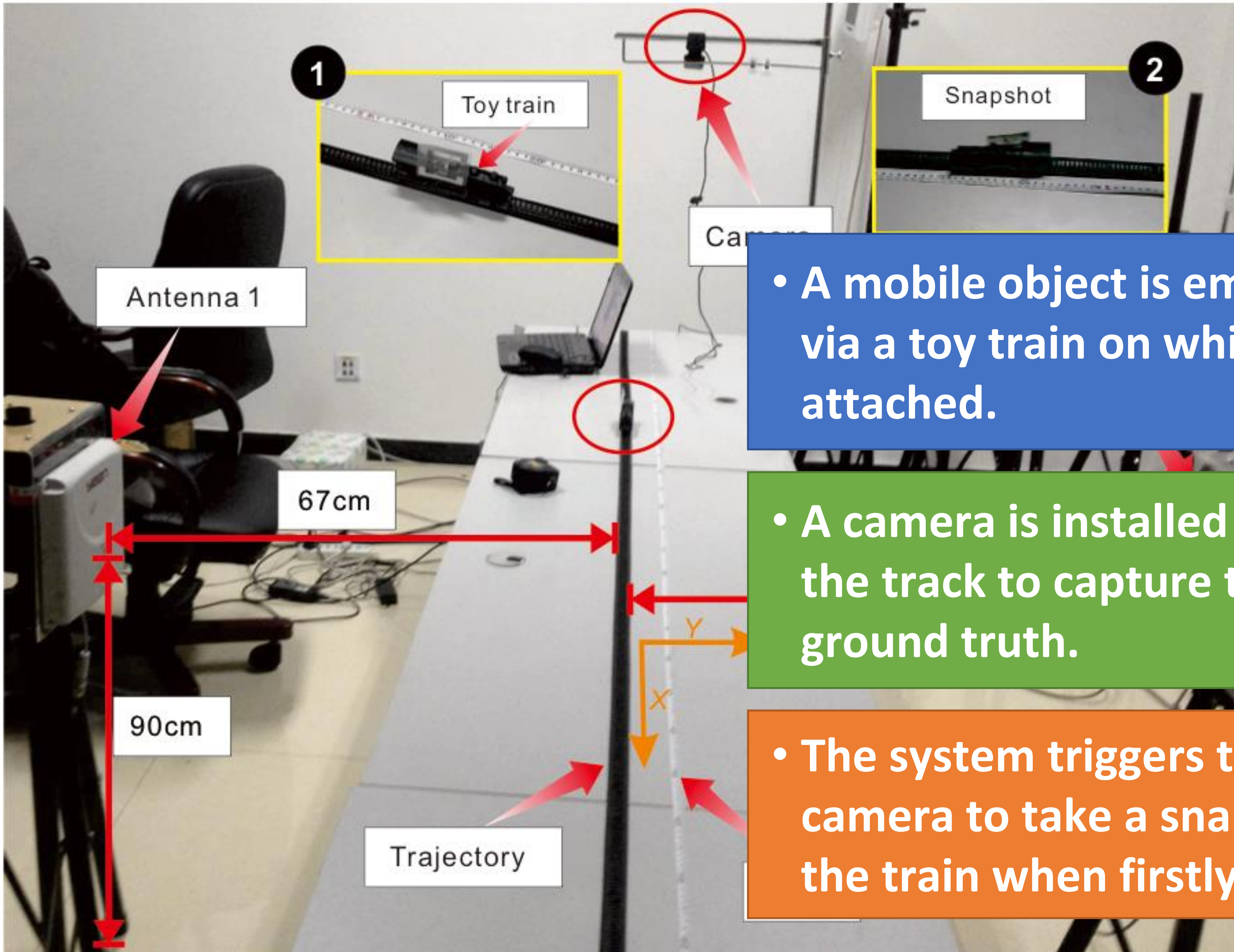
Alien Squiggle Inlay

Software

EPCglobal LLRP

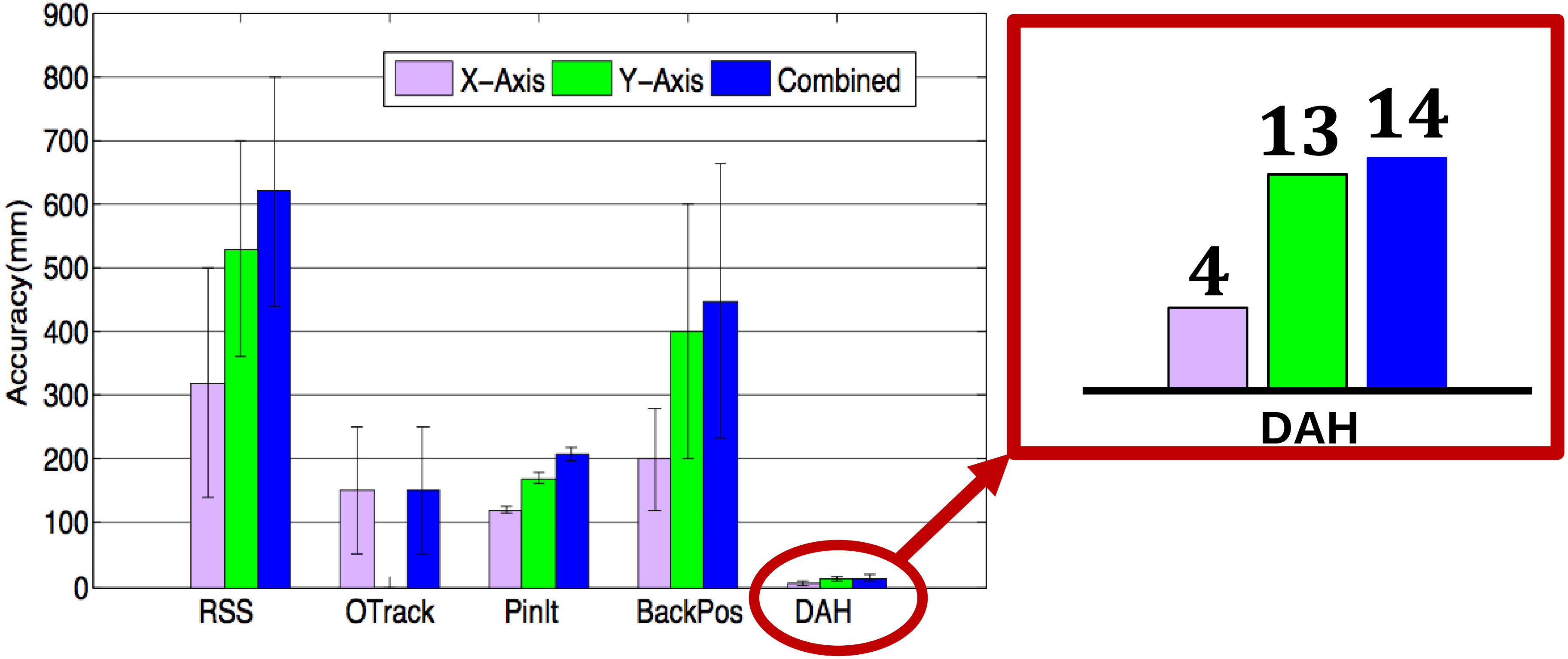
Java

Linear Track



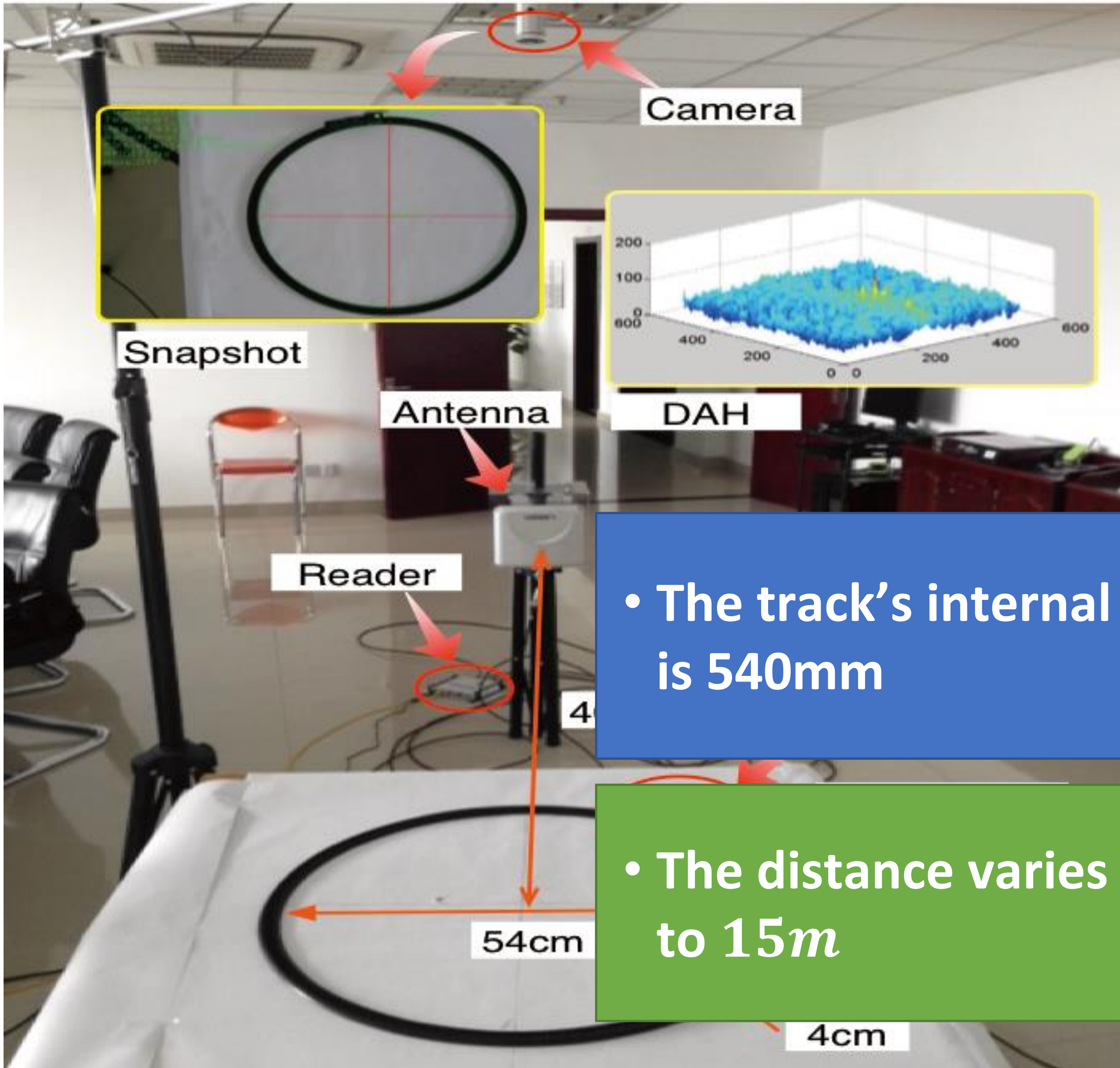
- A mobile object is emulated via a toy train on which a tag is attached.
- A camera is installed above the track to capture the ground truth.
- The system triggers the camera to take a snapshot on the train when firstly read.

Tracking Accuracy in Linear Track



Improve the accuracy by $48\times, 30\times, 28\times$ *and* $8.5\times$ in comparison to RSS, OTrack, PinIt and BackPos.

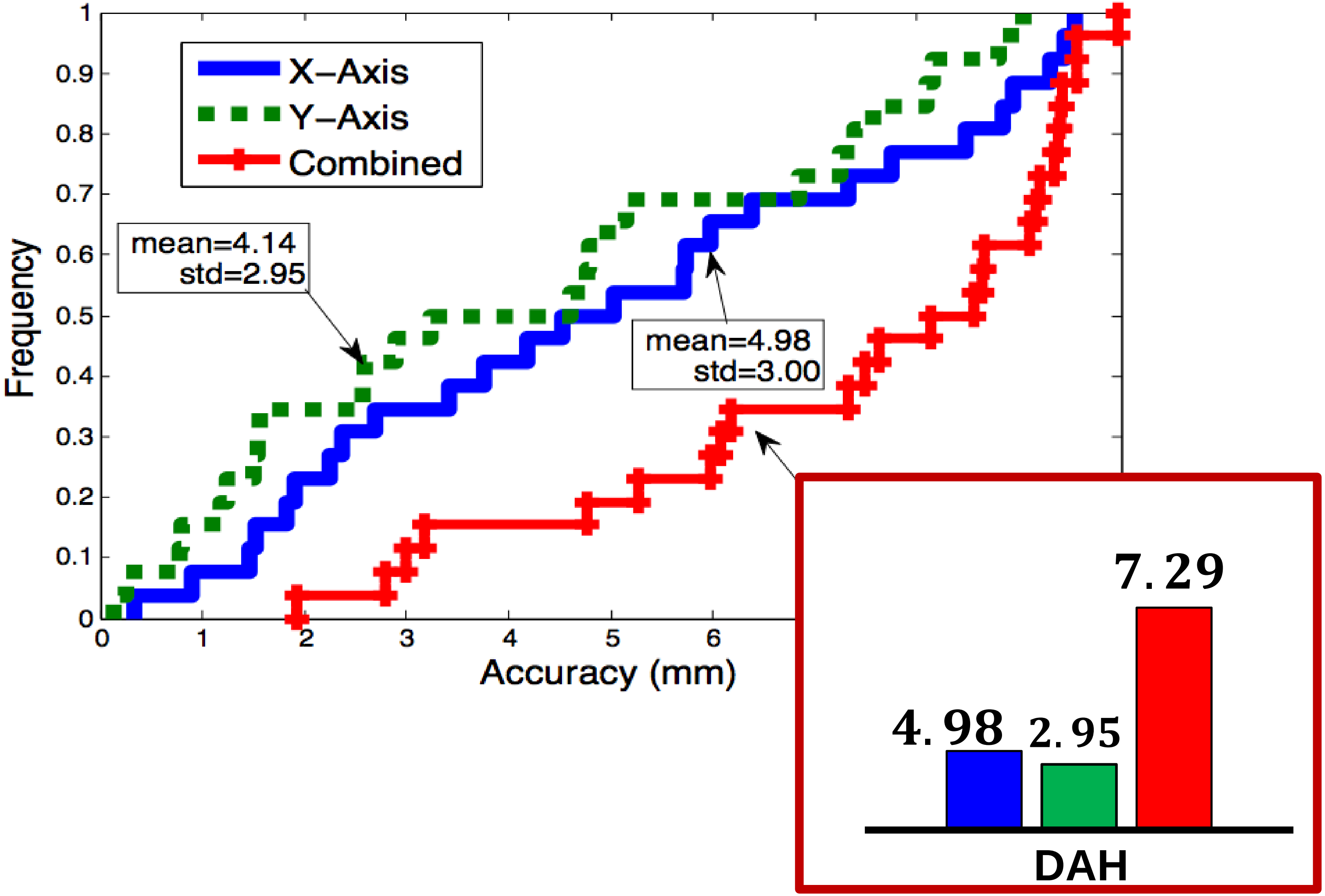
Controllable Case with Nonlinear Track



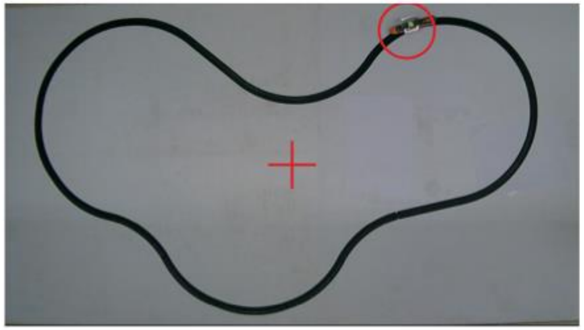
- **The track's internal diameter is 540mm**

- **The distance varies from $1m$ to $15m$**

Nonlinear track



Under Uncontrollable Case



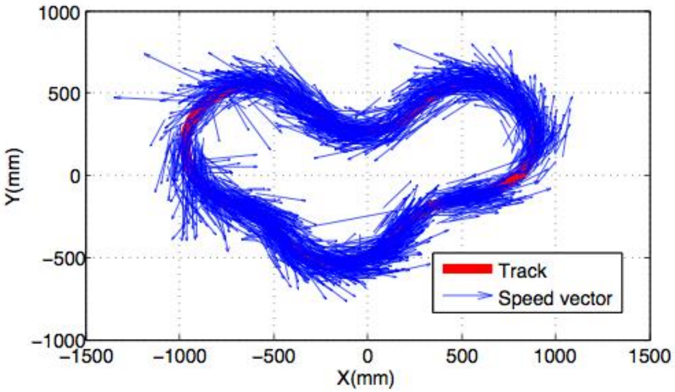


Figure 16: Estimated speed

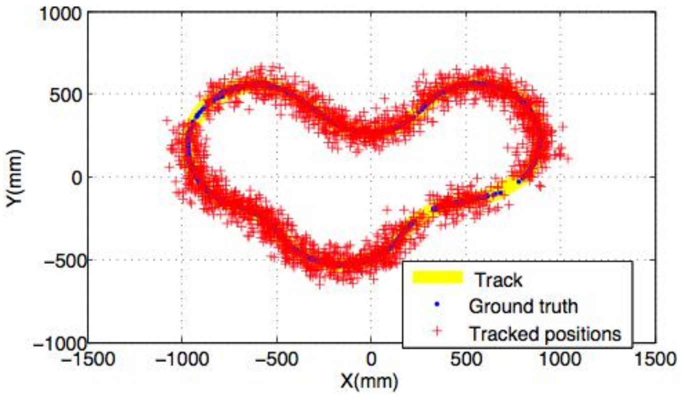


Figure 17: Fitted trajectory

Achieve a median of 12.3cm accuracy with a standard deviation of 5cm.

7 Pilot Study

In two airports

Current workflow – Manual sortation

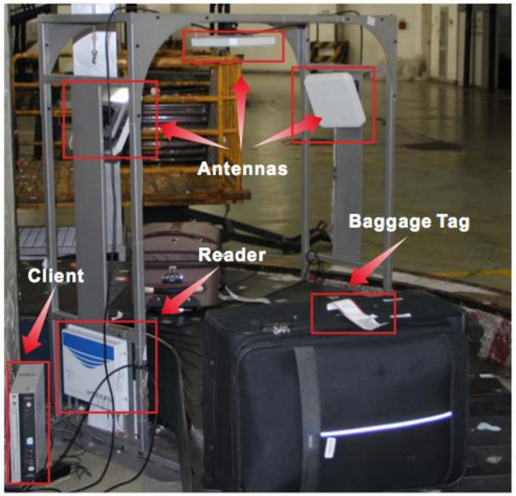
It is error-prone step to find the baggage from the carousel in manual sortation.

Sortation carousel

Sorting baggage

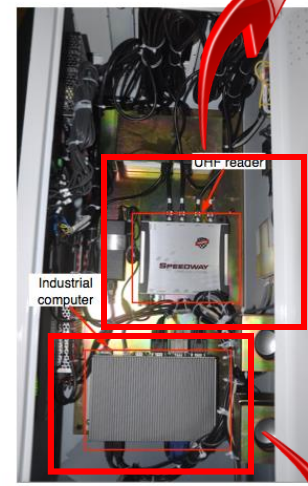
Our system: TrackPoint

Reader



(a) Version 1.0

(b) Version 2.0



(c) Internal structure

Industrial computer

(a) Two TrackPoints

(b) Version 2.0

Tracking Visualization

(a) TrackPoint & Visualization

(b) Display screen

(c) Screenshot

(d) TrackPoint & Visualization

Pilot site

Beijing Capital International Airport

Sanya Phoenix International Airport

Setup

- **Each airport contains 5 TrackPoints, 4 visualization screens, and 22 RFID Printers.**

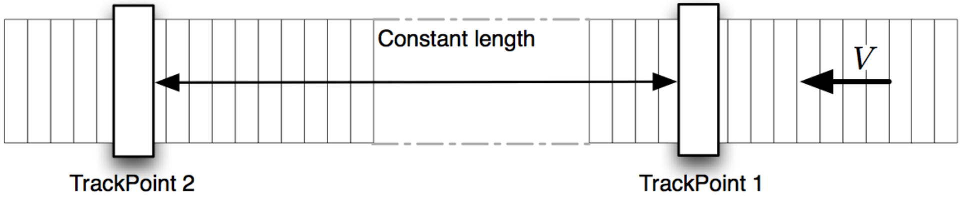
- **The two-year pilot study totally spent more than $600,000**

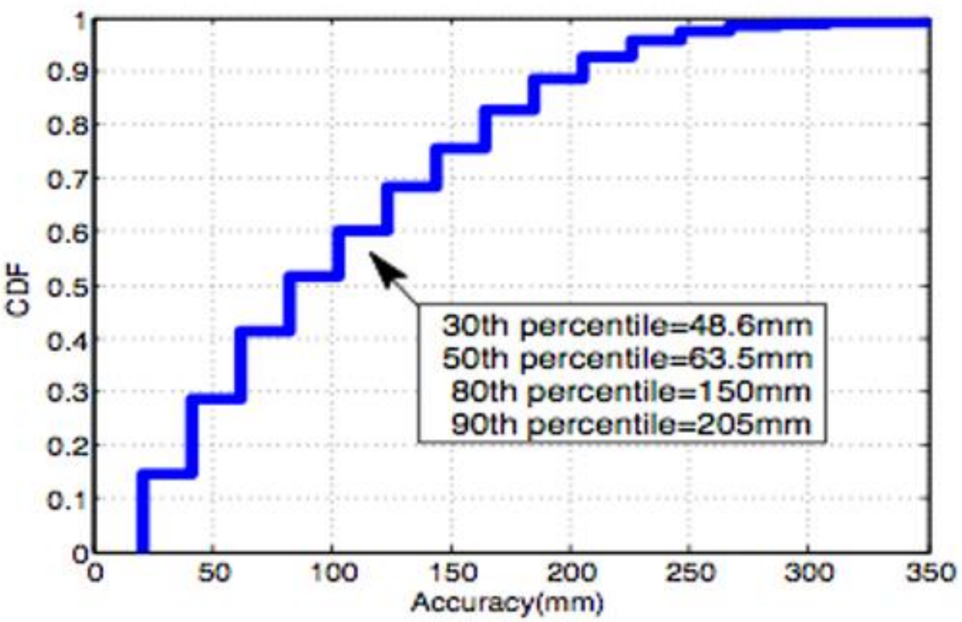
Setup

- Consumed 110,000 RFID tags.

- Involved 53 destination airports, 93 air lines, and 1,094 flights.

Tracking Accuracy





Tagoram achieves a median accuracy of 6.35cm in practice.

Conclusion

- **Provides real-time tracking of mobile tags with accuracy to mm-level.**
- **Limits almost all negative impacts.**
  - Multipath effect
  - Doppler effect
  - Thermal noise
  - Device diversity

  } *Not well-studied before*
- **Implemented purely based on COTS RFID products.**
- **Systematically evaluated under indoor environment and at two airports.**

Questions?

Thank you